Stochastic plasma "microtron"

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A sharp increase in the electron acceleration efficiency at a plasma resonance has been found experimentally upon the imposition of a weak magnetic field.

It has been shown theoretically[1,2] and experimentally[3] that electrons can be accelerated repeatedly at a plasma resonance.[4] Repeated acceleration was achieved in Ref. 3 by means of a linear sequence of localized resonances of the plasma field (an analog of a linear accelerator). The number of resonances was limited by the number of plasmoids that could be fitted into the aperture of the microwave pump field. This restriction is lifted when we switch to cyclic acceleration of a single plasmoid in a resonant

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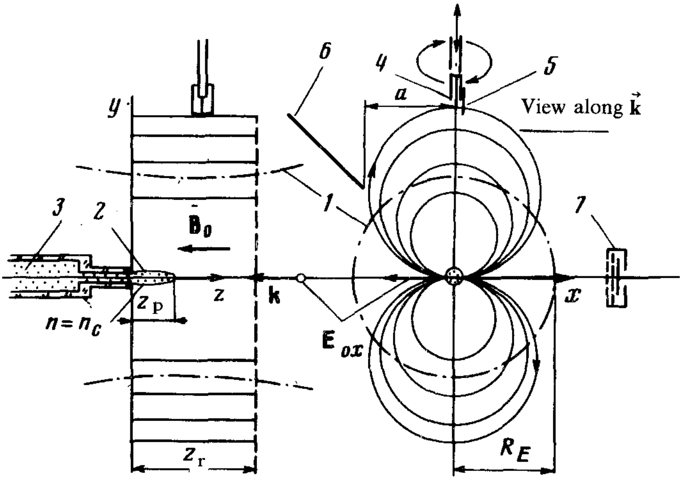

FIG. 1. The experimental arrangement.

field upon which a static magnetic field is imposed. An apparatus of this type has much in common with a microtron; a difference is that instead of a vacuum resonator we use a "plasma resonator" in which the electric field is significantly intensified, and the acceleration is stochastic. In the present letter we report experiments carried out in a weak magnetic field satisfying $\omega_B \ll \omega$, where $\omega_B = eB/mc$ is the electron gyrofrequency, and ω is the angular frequency of the microwave pump.

The experimental arrangement is shown in Fig. 1. The pulsed microwave source produces microwave power with a wavelength of 5 cm, an electric field $E_{0x} \lesssim 4$ kV/cm at the center of the focus $(x = y = z = 0)$, and a pulse length $\tau \lesssim 3$ μs. Dot-dashed line 1 in Fig. 1 shows the field boundary at the $e^{-1}E_{0x}$ level in side and front projections $(R_E \simeq 2.5$ cm). The plasma (2) is produced by the microwave power itself as it ionizes an argon jet injected into the vacuum chamber, at a pressure $\sim 10^{-4}$ torr (the chamber is being pumped down at a speed of 2×10^3 liter/s), from a narrow nozzle at the end of a ceramic tube (3), in which a pressure ~ 0.1 torr is maintained. Breakdown begins in the tube and then propagates to the free gas jet. After 3 μs, the plasmoid has a diameter ~ 0.2 cm and a length $z_p \simeq 0.8$ cm. The magnetic field B is varied from 0 to 70 G and is uniform within 5% over the interval $0 \leqslant z \leqslant 6$ cm. In the transverse direction, B falls off 14% at a radius of 15 cm.

Electrons are accelerated in the electric field of a plasma resonance in a plasma slab with a critical density $n_c = m\omega^2/4\pi e^2 \simeq 4.5 \times 10^{11}$ cm^{-3}. The direction in which the accelerated electrons are emitted in the case $B = 0$ is the direction of the electric field of the wave, E_{0x}. Figure 2a shows the electron energy spectrum for $B = 0$ (a plot of the current I_r drawn by probe 7 versus the retarding potential U_r). When a static magnetic field is applied, the accelerated electrons move along circles with a common point of tangency, where the field is the accelerating plasma-resonance field, as shown in Fig. 1. As the acceleration proceeds, the orbits of the electrons grow; specifically, the orbital radius ρ increases with increasing transverse electron energy $\mathscr{E} = mv_\perp^2/2$ in

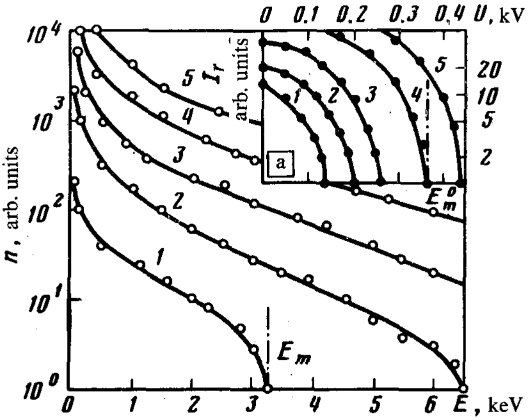

FIG. 2. Spectrum of accelerated electrons, $n(\mathscr{E})$, for $B = 70$ G and for various amplitudes of the alternating field, E_{0x}: 1—1; 2—1.5; 3—2; 4—3; 5—3.7 kV/cm. Inset a: The electron current I_r drawn by probe 7 versus the retarding potential U_r for $B = 0$.

accordance with $\rho = v_\perp/\omega_B = 3.35\sqrt{\mathscr{E}\,[\mathrm{eV}]}/B$ [G]. We can thus use the electron current density I measured with a movable probe 4 at various distances $y = 2\rho$ from the axis of the plasmoid to find the energy distribution of the accelerated electrons: $n(\mathscr{E}) \sim I/\sqrt{\mathscr{E}}$. The validity of this method for determining the electron energy distribution was confirmed by direct measurements of the electron energy by the retarding-potential method.

Several special experiments were carried out to verify that the motion of the electrons was actually as shown in Fig. 1. Probe 4, for example, was fitted with a shield 5 (Fig. 1) to demonstrate the unidirectional motion of the electrons (along the arrows) in sufficiently large orbits: $y > 3$ cm (at $E_{0x} \simeq 2$ kV/cm and $B \simeq 70$ G). This directed flux gives way to an isotropic flux near the plasmoid ($y < 1$ cm) because of collisions and the static electric field around the plasma, which causes a drift of the electrons in the crossed fields. The precise positions of the trajectories of the accelerated electrons were determined by placing various absorbing obstacles in the path of the electrons, e.g., limiters 6, which removed electrons with orbital radii $\rho > a$. The result was a cutoff of the current drawn by a probe at $y = 2a + 0.1$ cm. The same result was achieved when the wide limiter was replaced by a narrow strip 0.3 cm wide.

It is important to note that the current is also cut off when a narrow limiter is displaced from the plasmoid a distance $z < z_r \simeq 5$ cm along the direction of the magnetic field **B**. On the basis of this result we can assert that the electrons accelerated across **B** are trapped in the region $0 < z < z_r$ and that these electrons execute, in addition to a Larmor revolution in the (x,y) plane, an oscillatory motion along the axis $\mathbf{z} \| \mathbf{B}$. This oscillatory motion periodically returns them to the acceleration zone, $0 < z < z_p \simeq 0.8$ cm. The electrons are trapped in the region $z < z_r$ by the positive potential of the plasma. Direct measurements confirmed the existence of this potential, which was slightly higher than the energy of the thermal motion with $T_e \sim 30$–40 eV.

Figure 2 shows the results found on the electron energy spectra $n(\mathscr{E})$ from the

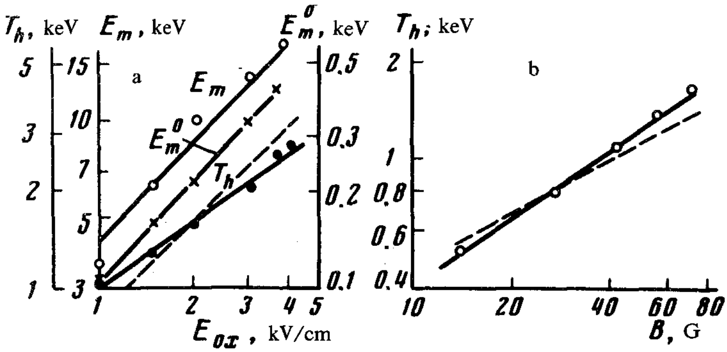

FIG. 3. Increase in the effective temperature T_h and in the cutoff energy of the spectra of accelerated electrons in a magnetic field $B = 70$ G ($\mathscr{E}_m$) and without a magnetic field, $B = 0$ ($\mathscr{E}_m^0$), with increasing alternating electric field (a) and increasing static magnetic field (b).

measured behavior of the current drawn by probe 4, $I(y)$. In a semilogarithmic plot these spectra have a linear region, so that they can be assigned an effective temperature T_h. The spectra also have a well-defined high-energy cutoff, so that we can identify a maximum acceleration energy $\mathscr{E}_m$. Figure 3a shows T_h and $\mathscr{E}_m$ at $B = 70$ G along with $\mathscr{E}_m^0$ (the maximum energy of the accelerated electrons in the absence of a magnetic field, $B = 0$) versus the pump field E_{0x}. Figure 3b shows the effective temperature T_h versus B for $E_{0x} \simeq 2$ kV/cm.

We used a method similar to that of Ref. 2 to determine the energy of the accelerated electrons during the repeated acceleration under these conditions. The effective temperature of the accelerated electrons under these experimental conditions can be described by

$$T_h = \mathscr{E}_m^0 \sqrt{N}, \qquad N \simeq (\omega_B t/\pi)(z_p/z_r).$$

Here $\mathscr{E}_m^0$ is the increment in the energy in the case of a single acceleration event in the absence of a magnetic field, and N is the average number of independent acceleration events over the time t (the probability for the electrons to be in the plasma-resonance region as they revolve in the magnetic field and oscillate along z is taken into account). We see that the repetition of the acceleration under these experimental conditions ($\omega_B \approx 10^9$ s^{-1}, $t \approx 10^{-6}$ s, $z_p/z_r \approx 0.2$, $N \propto 10^2$) increases T_h by nearly an order of magnitude. The behavior of T_h as a function of E_{0x} and B, shown by the dashed line in Fig. 3, corresponds satisfactorily to the experimental data. The theory also predicts a high-energy cutoff of the energy spectrum of the accelerated electrons, but the theoretical value of $\mathscr{E}_m$ depends strongly on the conditions under which the accelerated particles are confined. In the case of complete confinement, it is several times higher than the observed value.

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